MTL TR 87-22

AD

DTIC FILE COPY

AD-A183 019

MECHANICAL PROPERTY CHARACTERIZATION OF ESR 4353 STEEL WITH A COMPARISON TO ESR 4340 STEEL

TIMOTHY S. THOMAS and CHARLES F. HICKEY, Jr.
METALS RESEARCH DIVISION

April 1987

US ARMY
LABORATORY COMMAND
MATERIALS TECHNOLOGY
LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER MTL TR 87-22	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER A183019
4. TITLE (and Subtitle) MECHANICAL PROPERTY CHARACTERIZATION OF ESR 4353 STEEL WITH A COMPARISON TO ESR 4340 STEEL		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Timothy S. Thomas and Charles F. Hickey, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 ATTN: SLCMT-MCM		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L162105AH84 AMCMS Code: 612105.H8400
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12. REPORT DATE April 1987
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

4340 Steel (ESR)	Mechanical properties	Low alloy steels
Electroslag remelting	Toughness	
Heat treatment	Tempering	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE SIDE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block No. 20

ABSTRACT

The potential enhancement of ballistic and mechanical properties from electroslag remelting has fostered an interest in mechanical property characterizations of electroslag remelted (ESR) steels for Army applications. Mechanical property data are presented for quenched and tempered ESR 4353 and ESR 4340 steels. Hardness decreases from 61.1 to 44.4 ~~HRC~~ as tempering temperature increases from 300 to 900^{o}F for ESR 4353 steel. ~~Correspondingly~~, fracture toughness (K_{IQ}) increases from 23.4 ksi $\sqrt{in.}$ to 89.7 ksi ~~$\sqrt{in.}$~~ The ESR 4353 steel exhibits Charpy impact energy values of 12.4 ft-lb for 400 and 450^{o}F tempers, which decrease to 9.2 ft-lb for a 500^{o}F temper as a result of tempered martensite embrittlement. Percent retained austenite decreases to approximately zero as tempering temperature increases to 500^{o}F. Mechanical properties for similarly heat treated ESR 4340 steel are obtained from literature data. Results indicate that for a given tempering temperature or hardness, the ESR 4340 steel has greater Charpy impact energy and fracture toughness (K_{IQ}).

CONTENTS

A-1

INTRODUCTION

The U.S. Army Materials Technology Laboratory (MTL) has a major interest in the development and characterization of specially processed high strength steels for both helicopter and ground vehicle applications. Electroslag remelted (ESR) high strength steels have been of prime interest in recent years due to their enhanced ballistic and structural properties over those of comparable air-melted steels.[1-3] These superior properties are attributed primarily to the low sulfur content and homogeneous microstructural morphology which can be achieved by the electroslag remelting process.[4] Applications of electroslag remelted steels include ESR 4340 in the tail rotor pitch link assembly for the Army's advanced attack helicopter and ESR 4350 for the crew seat in the Blackhawk helicopter. ESR 4353 and ESR 300M were both considered as candidate materials in the suspension systems in the Army's M113A1 and XM2 track vehicles.[5]

In recent years, MTL has conducted a number of efforts on high strength ESR processed steels,[3,6-9] with prime emphasis on ESR 4340. This report addresses one such investigation on the mechanical properties of ESR 4353. Parameters pertinent for the consideration of high strength steels for Army applications include tensile properties, hardness, Charpy V-notch impact energy, fracture toughness (K_{IQ} and W/A), and percent retained austenite. These data were obtained as a function of tempering temperature over the range of 300 to 900°F. Also included in this report is a mechanical property comparison to the ESR 4340 steel, and other relevant MTL and literature data.

MATERIAL

The material examined was an air-melted heat of 4353 steel which had subsequently been argon-oxygen decarburized (AOD) and electroslag remelted (ESR). The chemical composition is given in Table 1. Three 5.5-foot-long, 1.9-inch-diameter hot-rolled and annealed bars of ESR 4353 steel were obtained from Simonds Steel. The anneal consisted of a 6- to 7-hour hold at 1450°F, a 12-hour furnace cool to 1150°F, and an air cool to room temperature. A hardness of HRC 97 was the result of this heat treatment.

Data included throughout this report for an ESR 4340 steel were obtained from Reference 6. This material was an argon-oxygen decarburized heat which was subsequently electroslag remelted. It was then processed into 5-inch-square cross section

1. ROHTERT, R. E. *Ballistic Design Support Tests - A Tool for Helicopter Vulnerability Reduction.* Presented at the AHS 31st Annual National Forum, Preprint No. 984, May 1975.
2. PRIFTI, J. J., PAPETTI, D., and RICCI, W. *ESR Steel/Kevlar Armored Bucket Seat for Aircrew Protection.* U.S. Army Materials Technology Labortory, Published in JTCG/AS Conference on Design of Armor Systems Proceedings, June 1983, (Confidential Report).
3. HICKEY, C. F., Jr., ANCTIL, A. A., and CHAIT, R. *The Ballistic Performance of High Strength 4340 Steel Processed by Electroslag Remelting.* Proceedings of Fracture Toughness of Wrought and Cast Steels, E. Fortner, ed., ASME MPC-13, 1980, p. 219-229.
4. PLOCKINGER, E. *Electroslag Remelting - A Modern Tool in Metallurgy.* Journal of the Iron and Steel Institute, August 1973.
5. GIBSON, D., BOERMAN, G., and GORUM, A. *High Strength Torsion Bar Development for Army Applications.* FMC Corporation, Contract DAAG46-76-C-0074, Final Report, AMMRC TR 79-5, January 1979.
6. HICKEY, C. F., Jr., and ANCTIL, A. A. *Split Heat Mechanical Property Comparison of ESR and VAR 4340 Steel.* U.S. Army Materials Technology Laboratory, AMMRC TR 83-27, May 1983.
7. HICKEY, C. F., Jr., THOMAS, T. S., and ANCTIL, A. A. *Comparison of Ballistic Performance of a Split Heat of ESR and VAR 4340 Steel.* U.S. Army Materials Technology Laboratory, AMMRC TR 85-20, July 1985.
8. ANCTIL, A. A., and RUDY, F. J. *Engineering and True Stress-Strain Tensile Properties of High Strength ESR 4340 and 4350 Steels.* U.S. Army Materials Technology Laboratory, AMMRC SP 75-9, November 1975.
9. ANCTIL, A. A. *Mechanical Properties and Fractography of Electroslag Remelted 300M Steel.* U.S. Army Materials Technology Laboratory, AMMRC TR 83-13, March 1983.

forgings. The chemical composition of the steel is given in Table 1. Further, mechanical property comparisons are made to heats of ESR 4340 and 4350 steel from which data were independently generated.[3,*]

Table 1. CHEMICAL COMPOSITIONS OF ESR 4353, ESR 4340[6], AND AISI 4340 STEELS (WEIGHT PERCENT)

Steel	C	Mn	Si	Ni	Cr	Mo	P	S	Al	Cu
ESR 4353	0.53	0.76	0.29	1.75	0.80	0.26	0.007	0.003	0.03	0.07
ESR 4340	0.41	0.70	0.26	1.73	0.90	0.22	0.008	0.001	0.035	0.21
AISI 4340	0.38-0.43	0.60-0.80	0.15-0.30	1.65-2.00	0.70-0.90	0.20-0.30	MAX 0.035	MAX 0.040		

PROCEDURE

Blanks for standard 0.394-inch-square cross section Charpy V-notch specimens of LT orientation were obtained from the ESR 4353 steel bars. These blanks were normalized at 1650°F for 2 hours and air cooled. They were then austenitized at 1550°F for 1 hour and quenched in 90°F oil. Sets of four blanks were tempered at each of the following temperatures for 3 hours: 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, and 900°F. Four hardness readings were taken on all specimens subsequent to final machining.

Room temperature Charpy impact energy data were obtained for two specimens from each tempering treatment. Precracked Charpy specimens were used to obtain fracture toughness data (K_{IQ} and W/A) for each tempering treatment. K_{IQ}, fracture toughness, is a conditional K_{IC} value and is obtained from the load-deflection curves for each specimen using the conventional stress intensity factor calculations for three-point bending. W/A is obtained by dividing the fracture energy by the area beneath the fatigue crack. Retained austenite measurements were made by X-ray analysis from fracture toughness specimens tempered at 350, 400, 450, and 500°F.

Blanks for six longitudinal 0.252-inch-diameter tensile bars and two transverse 0.113-inch-diameter tensile bars were taken from one of the ESR 4353 steel bars. Austenitizing and annealing treatments were the same for the Charpy V-notch blanks. Two of the longitudinal tensile blanks were tempered at 550°F for 3 hours. Two longitudinal and two transverse tensile blanks were double tempered at 550°F for 3 hours. After heat treatment, the blanks were machined to final size and tensile tested at room temperature.

According to Reference 6, blanks for 0.394-inch-square cross section Charpy V-notch specimens (LT and TL orientation), 0.394-inch-square cross section precracked Charpy specimens (LT and TL orientation), and 0.252-inch-diameter tensile bars (longitudinal and transverse orientation) were taken from the 5-inch-square cross section ESR 4340 steel forgings. These blanks were normalized at 1650°F for 1 hour and air cooled. They were then austenitized at 1550°F for 1 hour and oil quenched. Tempering treatments reported for these blanks were 325, 340, 500, 600, 800, 1000, and 1200°F for 1 hour. Reference 6 contains the corresponding Charpy impact energy, fracture toughness, and tensile data for the ESR 4340 steel heat treated accordingly.

*HICKEY, C. F., Jr., of U.S. Army Materials Technology Laboratory, Letter Communications with FMC Corporation, 1983 and 1984.

Irrespective of the slight difference in tempering time to data obtained for the ESR 4353 steel, only the data for which there is a direct comparison is included in this report. In terms of the resulting microstructure and mechanical properties, this investigation maintains that for a given tempering temperature there is no significant difference between a 1-hour and a 3-hour temper.

RESULTS AND DISCUSSION

Tensile Properties

Tensile data for ESR 4353 and ESR 4340 steels are tabulated in Table 2. There is no significant difference between the single and double tempered ESR 4350 longitudinal tensile properties. Anistropy is indicated by the lower reduction of area and tensile strength in double tempered transverse versus double tempered longitudinal specimens. Further, anistropy is revealed in ESR 4340 steel tempered at 400 and 500°F by the lower reduction of area in transverse specimens compared to longitudinal specimens. Note, that while ESR 4353 steel tempered at 550°F for 3 hours and the ESR 4340 steel tempered at 400°F for 1 hour have the same longitudinal tensile strength, the ESR 4340 steel so treated has a lower yield strength.

Table 2. EFFECT OF TEMPERING TEMPERATURE ON THE TENSILE PROPERTIES OF ESR 4340[6] AND ESR 4353 STEEL

ESR Steel	Temper, °F	Orientation	0.2% Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, %	Reduction of Area, %
4353	550 for 3 hr	L	249	286	11.0	45.2
		L	246	284	12.0	47.4
	Double Temper,	L	246	286	11.0	45.2
	550 for 3 hr	T	240	277	11.0	36.7
		T	243	274	9.0	34.5
4340	400 for 1 hr	L*	233	289	12.8	49.9
		T*	231	289	11.4	38.2
	500 for 1 hr	L*	227	270	12.4	51.2
		T*	228	268	11.0	42.7

*Represents average of 2 tests from standard 0.252-inch-diameter tensile bars.

Hardness as a function of tempering temperature for ESR 4353 and ESR 4340 steel is illustrated in Figure 1. For a given tempering temperature, the hardness of the ESR 4353 steel is greater than that of the ESR 4340 steel as expected from the former's higher carbon content.[10] In general, this difference decreases as tempering temperature increases.

Charpy Impact Energy

Room temperature Charpy impact energy is plotted as a function of tempering temperature in Figure 2. The embrittlement (tempered martensite embrittlement) in the 500 to 700°F range is well documented for 0.4% and 0.5% carbon steels[11] and, thus, expected for both 4353 and 4340 steel. It is clear that for a given temper within the 300 to 800°F range, the Charpy impact energy is much greater for the

10. BAIN, E. C., and PAXTON, H. W. *Alloying Elements in Steel*. American Society for Metals, Metals Park, Ohio, 2nd ed., 1961.
11. GROSSMAN, M. A., and BAIN, E. C. *Principles of Heat Treatment*. American Society for Metals, Metals Park, Ohio, 5th ed., 1964.

ESR 4340 steel than for the 4353 steel. These data, complemented by additional independently generated data on similarly treated 4350 steel,* emphasize the lower Charpy impact energy for a given temper for the higher carbon steel.

Fracture Toughness Parameters

Figures 3 and 4 illustrate W/A and K_{IQ} as a function of tempering temperature. For a given temper, ESR 4340 steel has a greater W/A and K_{IQ} than ESR 4353 steel. A rapid rise in W/A and K_{IQ} occurs for the ESR 4353 steel as tempering temperature

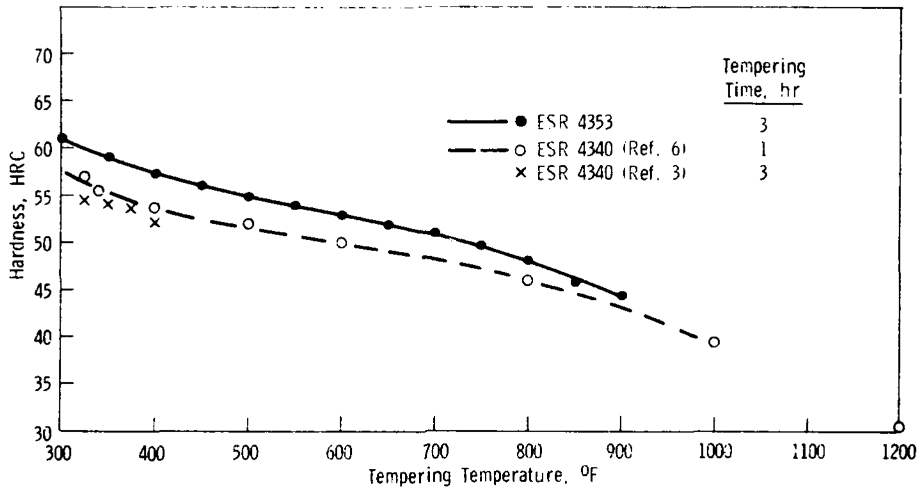
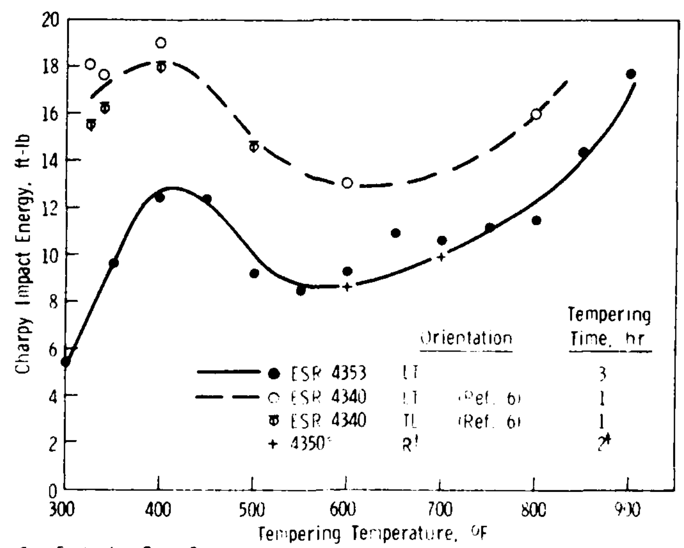


Figure 1. Hardness as a function of tempering temperature for ESR 4340 and ESR 4353 steel.

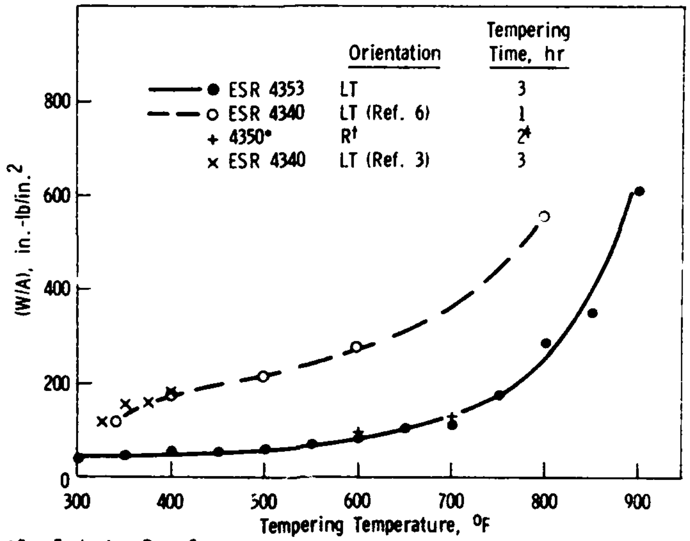


*See Footnote, Page 2
†Longitudinal Specimen with Notch in Radial Direction
‡Double Temper

Figure 2. Charpy impact energy as a function of tempering temperature for ESR 4340 and ESR 4353 steel.

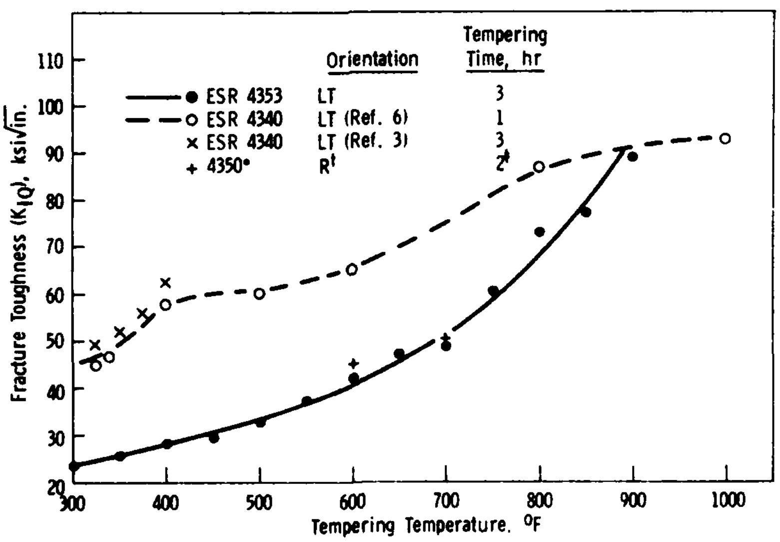
*HICKEY, C. F., Jr., of U.S. Army Materials Technology Laboratory, Letter Communications with FMC Corporation, 1983 and 1984.

increases above 700°F. A rapid rise for these two parameters occurs for the ESR 4340 steel as tempering temperature increases above 600°F, however, K_{IQ} levels off as tempering temperature approaches 800 to 1000°F. It is interesting to note that the 700°F temper produces a hardness of HRC 50 for the ESR 4353 steel, and the 600°F temper produces a nearly equivalent hardness of HRC 51 for the ESR 4340 steel.



*See Footnote, Page 2
†Longitudinal Specimen with Notch in Radial Direction
‡Double Temper

Figure 3. (W/A) as a function of tempering temperature for ESR 4340 and ESR 4353 steel.



*See Footnote, Page 2
†Longitudinal Specimen with Notch in Radial Direction
‡Double Temper

Figure 4. Fracture toughness as a function of tempering temperature for ESR 4340 and ESR 4353 steel.

Retained Austenite

Volume percent retained austenite in the ESR 4353 steel is tabulated in Table 3 as a function of tempering temperature. The amount of retained austenite decreases as tempering temperature increases, as is the case for similarly processed 4340 steel.[12]

Table 3. VOLUME PERCENT RETAINED AUSTENITE AS A FUNCTION OF TEMPERING TEMPERATURE FOR ESR 4353 STEEL*

Tempering Temperature, °F	Retained Austenite, Volume Percent
350	3.4
400	2.6
450	1.8
500	0

*Complete heat treatment consisted of 2-hour hold at 1650°F followed by an air cool; a 1-hour hold at 1550°F followed by an oil quench; and a 3-hour temper.

DISCUSSION

Figures 5, 6, and 7 present the toughness parameter data in a useful form for material selection, primarily when strength is a first consideration (insofar as hardness correlates with tensile strength).[13] It is shown that for a given hardness, the ESR 4340 steel has a greater Charpy impact energy, W/A, and K_{IQ} than ESR 4353 steel. Interestingly, it has also been observed that for a given tempering temperature, the ESR 4340 has greater Charpy impact energy, W/A, and K_{IQ} than ESR 4353 steel (Figures 2 through 4). These differences in mechanical properties are considered to be the result of microstructural responses associated with: (1) the greater carbon content of the higher carbon alloy (4353) and, (2) the correspondingly higher tempering temperatures necessary to achieve equivalent hardness as compared with the lower carbon alloy (4340). It is worthwhile to consider an example of the importance of the latter point. The stages of tempering martensite, as given by Speich,[14] define temperature ranges within which specific microstructural changes occur. The first stage is within the 212 to 482°F range, and the accompanying microstructural change includes the formation of epsilon or eta carbide(s). The microstructural response accompanying the second stage of tempering, 392 to 572°F, is the decomposition of retained austenite. From the relationships drawn in Figure 1, a hardness of approximately HRC 55 results from a 375°F temper for 4340 steel, and a 500°F temper for 4353 steel. With respect to the "tempering stages," it is clear that at HRC 55, these two steels must have different microstructures. Also, as has been shown, the 500°F temper is within the range of temperatures associated with tempered martensite embrittlement.

12. WILLIAMSON, D. L., SHUPMANN, R. G., MATERKOWSKI, J. P., and KRAUSS, G. *Determination of Small Amounts of Austenite and Carbide in a Hardened Medium Carbon Steel by Mossbauer Spectroscopy.* Met. Trans. A, v. 10A, 1976, p. 379-382.
13. DIETER, G. *Mechanical Metallurgy.* McGraw-Hill, Inc., 2nd ed., 1976.
14. SPEICH, G. R. *Tempered Ferrous Martensitic Structures.* Metals Handbook, American Society for Metals, Metals Park, Ohio, v. 8, 8th ed.

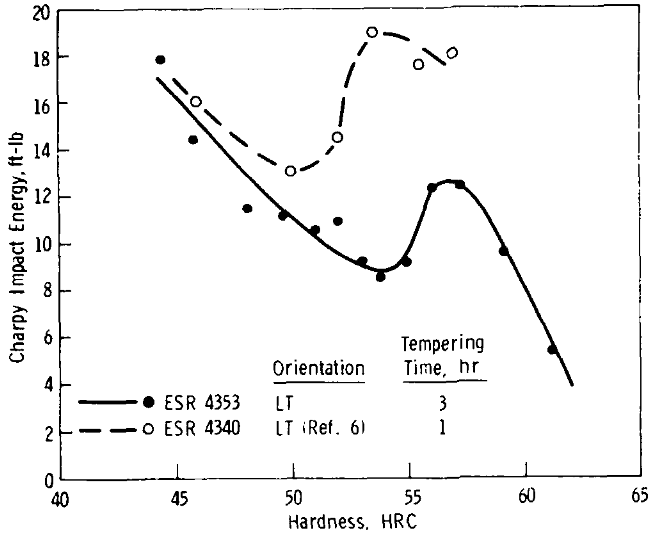


Figure 5. Charpy impact energy as a function of hardness for ESR 4340 and ESR 4353 steel.

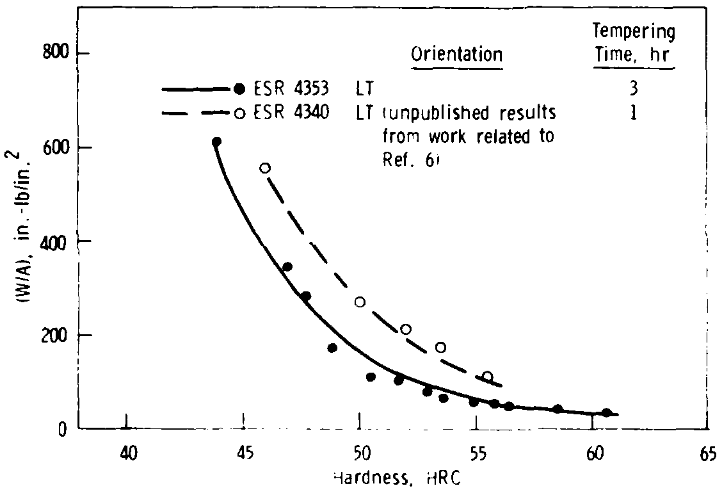


Figure 6. (W/A) as a function of hardness for ESR 4340 and ESR 4353 steel.

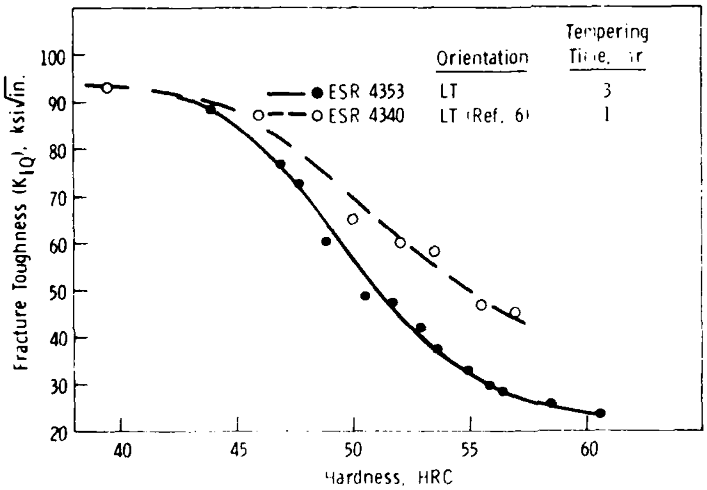


Figure 7. Fracture toughness as a function of hardness for ESR 4340 and ESR 4353 steel.

The advantage which ESR 4353 steel does possess over ESR 4340 steel is that greater hardnesses and, therefore, tensile strengths,[13] can be obtained in the former (Figure 1) because of its higher carbon content.[10] Tensile strength is often a mechanical property on which material selection depends. It is acknowledged that all applications do not require high fracture toughness and Charpy impact energy. In such a case, the high tensile strengths obtainable with ESR 4353 steel may prove useful.

Further, ESR 4353 steel tempered at 550°F for 3 hours, and ESR 4340 steel tempered at 400°F for 1 hour, have equivalent hardnesses (HRC 53.5) and tensile strengths (285 and 289 ksi, respectively). However, at HRC 53.5, the ESR 4353 has a yield strength of 247 ksi, while the ESR 4340 has a yield strength of 233 ksi. This evidence suggests that higher yield strengths are obtainable with the higher carbon 4353 steel for a given tensile strength, with respect to the heat treatments investigated. It is recognized that 4340 steel oil quenched and then tempered at 400°F for 1 hour should contain retained austenite, whereas 4353 steel oil quenched and then tempered at 550°F for 3 hours does not. If retained austenite could be removed in 4340 steel prior to the temper, e.g., by a liquid nitrogen quench, perhaps its resulting yield strength would increase.

It has been observed that rapid increases in the fracture toughness parameters occur for ESR 4353 steel as tempering temperature increases above 700°F and for ESR 4340 steel as tempering temperature increases above 600°F. These tempers produce hardnesses of 51 and 50 HRC, respectively. The rapid increases in these fracture toughness parameters may be a result of changes in both the materials' strength and microstructure as tempering temperature increases. First, tensile strength and yield strength decrease as tempering temperature increases, as is reflected in the hardness decreasing with increasing tempering temperature. For many alloys, it has been observed that K_I increases as yield strength decreases.[15] Second, interestingly, the 600 and 700°F tempers coincide, approximately, with the beginning of the third stage of tempering, about 482 to 660°F, as defined by Speich.[14] This is the beginning of the transition of martensite to cementite and ferrite.[16] Although it is not known to what extent such a resulting microstructure effects toughness parameters, it is clear from the literature that strength and microstructure are variables which may have a synergistic effect on toughness. The leveling off of K_{IQ} for ESR 4340 steel, as tempering temperature approaches 800 to 1000°F may in part result from the spheroidization of the cementite.

It is important to note that there are differences in the normalizing treatments for the ESR 4340[6] and ESR 4353 steels. This may have resulted in differences in grain size and carbide morphology which may not have otherwise been the case. To some extent, fracture toughness and Charpy impact energy are a function of these microstructural variables.[17-19]

15. HERTZBERG, R. W. *Deformation and Fracture Mechanics of Engineering Materials.* John Wiley and Sons, New York, 2nd ed., 1983.
16. CHALMERS, B. *Physical Metallurgy.* John Wiley and Sons, New York, 1959, p. 400.
17. COX, T. B., and LOW, J. R., Jr. *An Investigation of the Plastic Fracture of AISI 4340 and 18 Nickel--200 Grade Maraging Steels.* Met. Trans., June 1974, p. 1457-1470.
18. KAPADIA, B. M., ENGLISH, A. T., and BACKOFEN, W. A. *Influence of Mechanical Fibering on Brittle Fracture in Hot Rolled Steel Plate.* ASM Transactions Quarterly, September 1962, p. 389-398.
19. MRAVIC, B., and SMITH, J. H. *Development of Improved High-Strength Steels for Aircraft Structural Components.* AFML-TR-71-213, October 1971.

Another microstructural variable with the potential to affect the properties of 4340 and 4353 steels is retained austenite. Effects of retained austenite content on the properties of steels (e.g., wear resistance, hydrogen embrittlement susceptibility, and fracture toughness) have been the subject of many investigations.[20-22] Further, the heat treatment for tempering martensite (tempering and cooling) can transform austenite which has not decomposed upon tempering to extremely brittle untempered martensite. The purpose of double tempering is to temper martensite so formed.

Assuming austenite and martensite are the only microstructural constituents present in the as-quenched condition, retained austenite levels can be determined for steels from formulas which have been developed to solve for volume-percent martensite as a function of undercooling below the martensite start temperature (M_s). An equation by Andrews[23] predicts an M_s of 492°F for this ESR 4353 steel. With this M_s, Koistinen and Marburger's equation for volume-percent martensite[24] predicts 92 volume-percent martensite for the ESR 4353 steel quenched to 90°F and air cooled to 70°F. With respect to the aforementioned assumption, the as-quenched steel should contain 8 volume-percent retained austenite. The values of percent retained austenite in Table 3 are consistent with this result in that (1) they are of the same magnitude and (2) tempering decreases the amount of retained austenite.

It has been shown that a 570°F temper for 1 hour decreases the amount of retained austenite in quenched 4340 steel from approximately 4 volume-percent to zero percent.[12] Similarly, it is seen that a 500°F temper for 3 hours decreases the amount of retained austenite in ESR 4353 steel to zero percent (Table 3). Both results are consistent with the observation that the temperature range of 392 to 572°F defines the second stage of tempering where retained austenite completely decomposes. Double tempering of ESR 4353 steel, for the purpose mentioned previously, may therefore, have no practical application for a 550°F temper because there may be no austenite remaining to transform to martensite upon cooling. Thus, the equivalent tensile properties of ESR 4353 steel (Table 2), single and double tempered at 550°F, would be expected insofar as tensile properties are a function of percent-retained austenite (which is zero for both conditions).

SUMMARY

Longitudinal and transverse tensile properties, hardness, Charpy impact energy, fracture toughness (K_{IQ} and W/A), and percent-retained austenite are generated for ESR 4353 steel as a function of tempering temperature. Included is a comparison to data available in literature for similarly treated ESR 4340 steel. ESR 4353 steel tempered at 550°F for 3 hours and ESR 4340 steel tempered at 400°F for 1 hour has

20. SALESKY, W. J., and THOMAS, G. *Design of Medium-Carbon Steels for Wear Applications.* 1981-ASME, Wear of Materials Conference Proceedings, San Francisco, CA, 30 March - 1 April 1981, p. 298-305.
21. WOOD, W. E. *Effect of Retained Austenite on Hydrogen Embrittlement of Steels.* Oregon Graduate Center, ARO-13894.2-MS, AD-A078988, November 14, 1979, p. 18
22. SASTRY, C. N., and WOOD, W. E. *On the Presence of Retained Austenite at the Prior Austenite Grain Boundaries of AISI 4340 Steel.* Mater. Sci. Eng., October 1980, p. 277-280.
23. ANDREWS, K. W. *Empirical Formulae for the Calculation of Some Transformation Temperatures.* JISI, v. 203, 1965, p. 721-727.
24. KOISTINEN, D. P., and MARBURGER, R. E. *A General Equation Prescribing the Extent of the Austenite-Martensite Transformation in Pure Iron-Carbon Alloys and Plain Carbon Steels.* Acta. Met., v. 7, 1957, p. 59-60.

approximately the same tensile strength (285 and 289 ksi, respectively). However, the former's yield strength (247 ksi) is greater than the latter's (233 ksi). For a given tempering temperature within the 300 to 800°F range, the hardness of ESR 4353 (tempered for 3 hours) is greater than that of ESR 4340 steel (tempered for 1 hour). For a given hardness within the range of 46 to 57 HRC, ESR 4340 steel has greater or equal Charpy impact energy, K_{IQ}, and W/A, than ESR 4353 steel. Retained austenite decreases to zero percent as tempering temperature increases (3-hour tempers) from 350 to 500°F for ESR 4353 steel. The suitability of ESR 4353 as a substitute material is clarified by the data obtained and by the mechanical property comparison to the widely used ESR 4340 steel.

DISTRIBUTION LIST

No. of Copies	To
1	Office of the Under Secretary of Defense for Research and Engineering, The Pentagon, Washington, DC 20301
	Commander, U.S. Army Laboratory Command, 2800 Powder Mill Road, Adelphi, MD 20783-1145
1	ATTN: SLCIS-IM-TL
	Commander, Defense Technical Information Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, VA 22304-6145
2	ATTN: DTIC-FDAC
	Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
1	ATTN: J. H. Brown, Jr.
	Commander, Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709
1	ATTN: Information Processing Office
	Commander, U.S. Army Materiel Command (AMC), 5001 Eisenhower Avenue, Alexandria, VA 22333
1	ATTN: AMCLD
	Commander, U.S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD 21005
1	ATTN: AMXSY-MP, Director
	Commander, U.S. Army Missile Command, Redstone Arsenal, AL 35898
1	ATTN: Technical Library
1	AMSMI-CS, R. B. Clem
	Commander, U.S. Army Armament, Munitions and Chemical Command, Dover, NJ 07801
2	ATTN: Technical Library
	Commander, U.S. Army Tank-Automotive Command, Warren, MI 48090
1	ATTN: AMSTA-ZSK
2	AMSTA-TSL, Technical Library
1	AMSTA-RCK
	Commander, U.S. Army Foreign Science and Technology Center, 220 7th Street, N.E., Charlottesville, VA 22901
1	ATTN: Military Tech
	Director, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA 23604
1	ATTN: SAVDL-E-MOS (AVSCOM)
1	SAVDL-EU-TAP
	U.S. Army Aviation Training Library, Fort Rucker, AL 36360
1	ATTN: Building 5906--5907
	Commander, U.S. Army Aviation Systems Command, 4300 Goodfellow Boulevard, St. Louis, MO 63120
1	ATTN: AMDAV-EGX
1	AMDAV-EX, Mr. R. Lewis
1	AMDAV-EQ, Mr. Crawford
1	AMCPM-AAH-TM, Mr. R. Hubbard
1	AMDAV-DS, Mr. W. McClane
	Naval Research Laboratory, Washington, DC 20375
1	ATTN: Dr. C. I. Chang - Code 5830
1	Code 2627
	Chief of Naval Research, Arlington, VA 22217
1	ATTN: Code 471
	Director, Structural Mechanics Research, Office of Naval Research, 800 North Quincy Street, Arlington, VA 22203
1	ATTN: Dr. N. Perrone

No. of Copies	To
	Commander, U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, OH 45433
1	ATTN: AFWAL/MLC
1	AFWAL/MLLP, D. M. Forney, Jr.
1	AFWAL/MLBC, Mr. Stanley Schulman
1	AFWAL/MLXE, A. Olevitch
1	Edward J. Morrissey, AFWAL/MLTE, Wright Patterson Air Force Base, OH 45433
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, AL 35812
1	ATTN: R. J. Schwinghammer, EH01, Dir, M&P Lab
1	Mr. W. A. Wilson, EH41, Bldg. 4612
	Chief of Naval Operations, Washington, DC 20350
1	ATTN: OP-987, Director
	Aeronautical Systems Division (AFSC), Wright-Patterson Air Force Base, OH 45433
1	ATTN: ASD/ENFEF, D. C. Wight
1	ASD/ENFTV, D. J. Wallick
1	ASD/XRHD, G. B. Bennett
	Air Force Armament Laboratory, Eglin Air Force Base, FL 32542
1	ATTN: AFATL/DLYA, V. D. Thornton
	Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, OH 45433
1	ATTN: AFFDL/FES, G. W. Ducker
1	AFFDL/FES, J. Hodges
1	AFFDL/TST, Library
	Air Force Test and Evaluation Center, Kirtland Air Force Base, NM 87115
1	ATTN: AFTEC-JT
	NASA - Ames Research Center, Army Air Mobility Research and Development Laboratory, Mail Stop 207-5, Moffett Field, CA 94035
1	ATTN: SAVDL-AS-X, F. H. Immen
	NASA - Johnson Spacecraft Center, Houston, TX 77058
1	ATTN: JM6
1	ES-5
	Naval Air Development Center, Warminster, PA 18974
1	ATTN: Code 063
	Naval Air System Command, Department of the Navy, Washington, DC 20360
1	ATTN: AIR-03PAF
1	AIR-5203
1	AIR-5204J
1	AIR-530313
	Naval Material Command, Washington, DC 20360
1	ATTN: MAT-0331
	Naval Post Graduate School, Monterey, CA 93948
1	ATTN: Code 57BP, R. E. Ball
	Naval Surface Weapons Center, Dahlgren Laboratory, Dahlgren, VA 22448
1	ATTN: Code G-54, Mr. J. Hall
1	Code G-54, Mr. E. Rowe
	Naval Weapons Center, China Lake, CA 93555
1	ATTN: Code 40701
1	Code 408
	Commander, Rock Island Arsenal, Rock Island, IL 61299
1	ATTN: AMSAR-PPV
	Armament Systems, Inc., 712-F North Valley, Anaheim, CA 92801
1	ATTN: J. Musch

No. of Copies	To
	Beech Aircraft Corporation, 9709 E. Central Avenue, Wichita, KS 67206
1	ATTN: Engineering Library
	Bell Helicopter Company, A Textron Company, P.O. Box 482, Fort Worth, TX 76101
1	ATTN: J. R. Johnson
	Boeing Vertol Company, A Division of the Boeing Company, P.O. Box 16858, Philadelphia, Philadelphia, PA 19142
1	ATTN: J. E. Gonsalves, M/S P32-19
1	Cessna Military, P.O. Box 7704, Wichita, KS 67277-7704
	Fairchild Industries, Inc., Fairchild Republic Company, Conklin Street, Farmingdale, Long Island, NY 11735
1	ATTN: Engineering Library, G. A. Mauter
	FMC Corporation, Central Engineering Labs, 1185 Coleman Avenue, Box 80, Santa Clara, CA 95052
1	ATTN: Gary L. Boerman
	FMC Corporation, Ordnance Division, 1105 Coleman Avenue, Box 1201, San Jose, CA 95108
1	ATTN: William H. Altergott
	General Dynamics Corporation, Convair Division, P.O. Box 80877, San Diego, CA 92138
1	ATTN: Research Library, U. J. Sweeney
	Gruman Aerospace Corporation, South Oyster Bay Road, Bethpage, NY 11714
1	ATTN: Technical Information Center, J. Davis
	Hughes Helicopters, A Division of Summa Corporation, Centinela & Teale Street, Culver City, CA 90230
1	ATTN: Library, 2/T2124, D. K. Coss
1	Mr. A. Hirko
1	Mr. L. Soffa
	IIT Research Institute, 10 West 35th Street, Chicago, IL 60616
1	ATTN: K. McKee
	Kaman Aerospace Corporation, Old Winsor Road, Bloomfield, CT 06002
1	ATTN: H. E. Showalter
	Lockheed-California Company, A Division of Lockheed Aircraft Corporation, Burbank, CA 91503
1	ATTN: Technological Information Center, 84-40, U-35, A-1
	Vought Corporation, P.O. Box 5907, Dallas, TX 75232
1	ATTN: D. M. Reedy, 2-30110
1	M. P. Poullos, Jr.
	Martin Marietta Corporation, Orlando Division, P.O. Box 5837, Orlando, FL 32805
1	ATTN: Library, M. C. Griffith
	McDonnell Douglas Corporation, 3855 Lakewood Boulevard, Long Beach, CA 90846
1	ATTN: Technical Library, Cl 290/36-84
	Northrop Corporation, Aircraft Division, 3901 W. Broadway, Hawthorne, CA 90250
1	ATTN: Mgr. Library Services, H. W. Jones
	Parker Hannifin Corporation, Bertea Control Systems Division, 18001 Von Karman Avenue, Irvine, CA 92715
1	ATTN: C. Beneker
	Rockwell International Corporation, Los Angeles Aircraft Division, B-1 Division, International Airport, Los Angeles, CA 90009
1	ATTN: W. L. Jackson

No. of Copies	To
	Sikorsky Aircraft, A Division of United Aircraft Corporation, Main Street, Stratford, CT 06601
1	ATTN: J. B. Fauik
1	Mel Schwartz, Chief of Metals
	Teledyne CAE, 1330 Laskey Road, Toledo, OH 43697
1	ATTN: Librarian, M. Dowdell
	Simonds Steel Division, Guterl Special Steel Corporation, Lockport, NY 14094
1	ATTN: Mr. R. Farrington
	Atlas Testing Laboratories, Inc., 6929 E. Slauson Avenue, Los Angeles, CA 90040
1	ATTN: Mr. P. S. Horvath
	Georgia Institute of Technology, School of Mechanical Engineering, Atlanta, GA 30332
1	ATTN: Dr. J. T. Berry
	Lukens Steel Company, Coatesville, PA 19320
1	ATTN: Dr. E. Hamburg
	Republic Steel Corporation, 410 Oberlin Avenue SW, Massillon, OH 44646
1	ATTN: Mr. R. Sweeney
1	Mr. W. H. Brechtel
1	Mr. T. M. Costello
	Boeing Commercial Airplane Company, P.O. Box 3707, MS73-43, Seattle, WA 98124
1	ATTN: Dr. K. White
	METTEC, 1805 E. Carnegie Avenue, Santa Ana, CA 92705
1	ATTN: Dr. L. Raymond
	Ingersoll Rand Oilfield Products Division, P.O. Box 1101, Pampa, TX 79065
1	ATTN: Mr. W. L. Hallerberg
	Brown University, Division of Engineering, Providence, RI 02912
1	ATTN: Prof. J. Duffy
	SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025
1	ATTN: Dr. D. Shockey
	Illinois Institute of Technology, Metallurgical and Materials Engineering Department, Chicago, IL 60616
1	ATTN: Dr. Norman Breyer
	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
2	ATTN: SLCMT-IML
2	Authors

U.S. Army Materials Technology Laboratory,
Watertown, Massachusetts 02172-0001
MECHANICAL PROPERTY CHARACTERIZATION OF
ESR 4353 STEEL WITH A COMPARISON TO
ESR 4340 STEEL -
Timothy S. Thomas and Charles F. Hickey, Jr.

Technical Report MTL TR 87-22, April 1987, 13 pp -
illus-tables, D/A Project: 1L162105AH84,
AMCMS Code: 612105.H8400

AD__________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

4340 Steel (ESR)
Electroslag remelting
Heat treatment

The potential enhancement of ballistic and mechanical properties from electroslag remelting has fostered an interest in mechanical property characterizations of electroslag remelted (ESR) steels for Army applications. Mechanical property data are presented for quenched and tempered ESR 4353 and ESR 4340 steels. Hardness decreases from 61.1 to 44.4 HRC as tempering temperature increases from 300 to 900°F for ESR 4353 steel. Correspondingly, fracture toughness (K_{IQ}) increases from 23.4 ksi $\sqrt{in.}$ to 89.7 ksi $\sqrt{in.}$ The ESR 4353 steel exhibits Charpy impact energy values of 12.4 ft-lb for 400 and 450°F tempers, which decrease to 9.2 ft-lb for a 500°F temper as a result of tempered martensite embrittlement. Percent retained austenite decreases to approximately zero as tempering temperature increases to 500°F. Mechanical properties for similarly heat treated ESR 4340 steel are obtained from literature data. Results indicate that for a given tempering temperature or hardness, the ESR 4340 steel has greater Charpy impact energy and fracture toughness (K_{IQ}).

U.S. Army Materials Technology Laboratory,
Watertown, Massachusetts 02172-0001
MECHANICAL PROPERTY CHARACTERIZATION OF
ESR 4353 STEEL WITH A COMPARISON TO
ESR 4340 STEEL -
Timothy S. Thomas and Charles F. Hickey, Jr.

Technical Report MTL TR 87-22, April 1987, 13 pp -
illus-tables, D/A Project: 1L162105AH84,
AMCMS Code: 612105.H8400

AD__________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

4340 Steel (ESR)
Electroslag remelting
Heat treatment

The potential enhancement of ballistic and mechanical properties from electroslag remelting has fostered an interest in mechanical property characterizations of electroslag remelted (ESR) steels for Army applications. Mechanical property data are presented for quenched and tempered ESR 4353 and ESR 4340 steels. Hardness decreases from 61.1 to 44.4 HRC as tempering temperature increases from 300 to 900°F for ESR 4353 steel. Correspondingly, fracture toughness (K_{IQ}) increases from 23.4 ksi $\sqrt{in.}$ to 89.7 ksi $\sqrt{in.}$ The ESR 4353 steel exhibits Charpy impact energy values of 12.4 ft-lb for 400 and 450°F tempers, which decrease to 9.2 ft-lb for a 500°F temper as a result of tempered martensite embrittlement. Percent retained austenite decreases to approximately zero as tempering temperature increases to 500°F. Mechanical properties for similarly heat treated ESR 4340 steel are obtained from literature data. Results indicate that for a given tempering temperature or hardness, the ESR 4340 steel has greater Charpy impact energy and fracture toughness (K_{IQ}).

U.S. Army Materials Technology Laboratory,
Watertown, Massachusetts 02172-0001
MECHANICAL PROPERTY CHARACTERIZATION OF
ESR 4353 STEEL WITH A COMPARISON TO
ESR 4340 STEEL -
Timothy S. Thomas and Charles F. Hickey, Jr.

Technical Report MTL TR 87-22, April 1987, 13 pp -
illus-tables, D/A Project: 1L162105AH84,
AMCMS Code: 612105.H8400

AD__________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

4340 Steel (ESR)
Electroslag remelting
Heat treatment

The potential enhancement of ballistic and mechanical properties from electroslag remelting has fostered an interest in mechanical property characterizations of electroslag remelted (ESR) steels for Army applications. Mechanical property data are presented for quenched and tempered ESR 4353 and ESR 4340 steels. Hardness decreases from 61.1 to 44.4 HRC as tempering temperature increases from 300 to 900°F for ESR 4353 steel. Correspondingly, fracture toughness (K_{IQ}) increases from 23.4 ksi $\sqrt{in.}$ to 89.7 ksi $\sqrt{in.}$ The ESR 4353 steel exhibits Charpy impact energy values of 12.4 ft-lb for 400 and 450°F tempers, which decrease to 9.2 ft-lb for a 500°F temper as a result of tempered martensite embrittlement. Percent retained austenite decreases to approximately zero as tempering temperature increases to 500°F. Mechanical properties for similarly heat treated ESR 4340 steel are obtained from literature data. Results indicate that for a given tempering temperature or hardness, the ESR 4340 steel has greater Charpy impact energy and fracture toughness (K_{IQ}).

U.S. Army Materials Technology Laboratory,
Watertown, Massachusetts 02172-0001
MECHANICAL PROPERTY CHARACTERIZATION OF
ESR 4353 STEEL WITH A COMPARISON TO
ESR 4340 STEEL -
Timothy S. Thomas and Charles F. Hickey, Jr.

Technical Report MTL TR 87-22, April 1987, 13 pp -
illus-tables, D/A Project: 1L162105AH84,
AMCMS Code: 612105.H8400

AD__________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

4340 Steel (ESR)
Electroslag remelting
Heat treatment

The potential enhancement of ballistic and mechanical properties from electroslag remelting has fostered an interest in mechanical property characterizations of electroslag remelted (ESR) steels for Army applications. Mechanical property data are presented for quenched and tempered ESR 4353 and ESR 4340 steels. Hardness decreases from 61.1 to 44.4 HRC as tempering temperature increases from 300 to 900°F for ESR 4353 steel. Correspondingly, fracture toughness (K_{IQ}) increases from 23.4 ksi $\sqrt{in.}$ to 89.7 ksi $\sqrt{in.}$ The ESR 4353 steel exhibits Charpy impact energy values of 12.4 ft-lb for 400 and 450°F tempers, which decrease to 9.2 ft-lb for a 500°F temper as a result of tempered martensite embrittlement. Percent retained austenite decreases to approximately zero as tempering temperature increases to 500°F. Mechanical properties for similarly heat treated ESR 4340 steel are obtained from literature data. Results indicate that for a given tempering temperature or hardness, the ESR 4340 steel has greater Charpy impact energy and fracture toughness (K_{IQ}).

DEPARTMENT OF THE ARMY
U.S. ARMY LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY
ATTN: SLCMT-IMA-P
Watertown, Massachusetts 02172-0001

Commander
Defense Technical Information Center
Cameron Station, Building 5
5010 Duke Street
Alexandria, VA 22304-6145
ATTN: DTIC-FDAC